Micro-machinability and Edge Chipping Mechanism Studies on Diamond Micro-milling of Monocrystalline Silicon

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Abstract

Excessive generation of undesirable surface and subsurface damages such as surface edge chipping often occurs when monocrystalline silicon, a hard and brittle material, is machined at tens to hundreds of microns in thickness. However, before developing strategies to reduce edge chipping and improve the machining efficiency by micro-milling, understanding of its cutting mechanism is required. In this study, the micro-machinability and edge chipping mechanism on a (001) silicon were investigated by full slot milling using the natural diamond tool. A volumetric measurement technique was also proposed to quantify edge chipping better. Three chipping types: 45°, 90° and mixed mode (dominant type) were observed, and its mechanism is attributed to cleavage and slip structure within silicon's crystal architecture. The cutting forces, surface and edge quality were examined and characterised accordingly. From the reported results, the size effect on the specific cutting energy is greatly influenced by the shear strain work hardening of the workpiece. Enhancement of the strain work hardening effect is attributed and demonstrated using small feed rate, high cutting speed and cutting along the [100] feed direction. As a result, good surface quality of $R_a = 20$ nm and small edge chipping volume of $80 \mu m^3$ were achieved.

Keywords: Micro-machinability, diamond machining, micro-milling, monocrystalline silicon, edge chipping, ductile mode cutting, chip adhesion, tool wear
1. Introduction

Silicon is a hard and brittle material. Its structural properties like fracture toughness, hardness, and Young’s modulus are affected by both the crystalline orientation and temperature. Silicon reigns itself on various applications such as solid-state devices in microelectronics industries, photonic systems, and medical implants. Some applications require silicon to be fabricated into 3D microstructures at tens to hundreds of micrometres in thickness with high accuracy and surface quality for functional purposes. Typical techniques such as deep reactive ion etching (DRIE) and wet etching are used. Mechanical processes such as grinding, lapping, and polishing are also used but are limited to planar structures.

In contrast, mechanical micro-milling offers simple setup with high accuracy and 3D machining capability. Recently, it was successfully applied to shape brittle materials, such as lithium niobate [1], monocrystalline silicon [2–4], ceramics [5] and glass [6–7] with minimised defects. Hence, micro-milling is expected to become an alternative maskless approach for fabricating complex 3D silicon-based devices with feature size at the order of several tens to hundreds of micrometres. Unlike ductile materials, brittle materials fracture easily due to low fracture toughness and are hard to machine. However, research shows that brittle materials could deform plastically under some conditions [8–10].

Stringent control of machining conditions such as using cutting tool with negative rake angle and exceptionally small uncut chip thickness and cutting edge radius (at sub-micron levels) are often required. Although mechanical micro-milling shows potential in producing a 3D freeform structure with minimised defects, machining conditions used by previous researchers were not comparable to the advantages offered by lithography techniques. Subsequently, Huo et al. [11] and Choong et al. [12] had demonstrated the capability of achieving good machining quality on silicon by mechanical micro-milling with enhanced parameters. Furthermore, the surface generated on mechanically machined silicon are also affected by the feed directions [13–15].

Currently, two issues limit the use of mechanical micro-milling to shape or singulate functional 3D microstructures on a silicon wafer. Firstly, excessive surface and subsurface defects such as edge chipping and micro-fractures as shown in Figure 1 may develop when silicon is shaped at tens to hundreds of micrometres in thickness. As such, minimisation of such defects is required to prevent functionality and structural failure of the finished product. Secondly,
machining parameters used by previous researchers in ductile mode cutting of silicon deems to be very time consuming as extremely small (at several nanometres) feed rate and depth of cut were used [16].

By considering the insufficient experimental data on the cutting performances and edge chipping mechanism of micro-milled silicon, this research aims to investigate the micro-machinability like tool quality, cutting forces and surface generation during silicon mechanical micro-milling by diamond machining. Also, a volumetric measurement method was proposed due to the absence of a guideline to quantify edge chipping. The organisation of this paper is as follows: Section 2 begins by reviewing the mechanism of ductile mode cutting in silicon by mechanical micro-milling, while the experimental methods are described in Section 3. Subsequently, results are presented and discussed qualitatively and quantitatively in Section 4. Finally, conclusions from this research are drawn in Section 5.

![Figure 1: Schematic of a machined channel with machining-induced edge chipping and surface micro-fractures.](image)
2. The realisation of Ductile Mode Cutting in Silicon Micro-milling

Ductile mode cutting can be realised during material removal by plastic deformation while inhibiting the machining-induced defects to propagate with stringent control of machining parameters. Figure 2 illustrates the relationship between the feed rate, \( f_z \), and subsurface damage depth, \( l_c \), during up-milling. As the uncut chip thickness, \( t_m \), increases from zero, ploughing occurs until the critical chip thickness, \( t_c \), is reached for effective cutting action and chip formation.

![Diagram showing the relationship between feed rate and subsurface damage depth during up-milling.](image)

**Figure 2:** Relationship between the feed rate, \( f_z \), and subsurface damage depth, \( l_c \), during up-milling for (a) small feed rate and (b) large feed rate.

Depending on the feed rate, \( f_z \), the fracture will occur along the cut shoulder, when the tool cutting edge surpasses the ductile to brittle transition chip thickness, \( t_d \), under a certain critical angle, \( \theta_d \) [17]. For a small \( f_z \), the subsurface damage depth, \( l_c \), will be longer as the brittle transition chip thickness, \( t_d \), will only be reached at the upper edge of the cut shoulder. Hence, the fracture can be removed by subsequent tool passes. Conversely, higher feed rate, \( f_z \), will force the fracture to generate closer to the final machined surface, thus making it impossible to be removed by subsequent tool passes.

Theory of plasticity also suggests that the magnitude of hydrostatic pressure generated within the cutting zone is another enabling factor that dictates the extent of plastic deformation during material removal [18]. When the effective rake angle, \( \gamma_e \), turns large and negative, the material ahead of the cutting tool will be compressed under a large hydrostatic pressure [10]. As shown in Figure 3, the effective rake angle, \( \gamma_e \), can be computed by Equations 1 and 2 [19]:

\[ \text{Equation 1} \]

\[ \text{Equation 2} \]
a) when the uncut chip thickness, \( t_m \leq r_e (1 + \sin \gamma) \):

\[
\gamma_e = -\frac{\pi}{2} + \tan^{-1} \frac{t_m}{\sqrt{(2r_e - t_m)t_m}}
\]  

\( (1) \)

b) when the uncut chip thickness, \( t_m > r_e (1 + \sin \gamma) \):

\[
\gamma_e = -\frac{\pi}{2} + \tan^{-1} \frac{t_m}{(r_e(1 + \sin \gamma) - t_m) \tan \gamma + r_e \cos \gamma}
\]  

\( (2) \)

Even at a nominal rake angle, \( \gamma = 0^\circ \), Equations 1 and 2 shows that the effective rake angle, \( \gamma_e \), turns large and negative when the cutting edge radius, \( r_e \), increases and uncut chip thickness, \( t_m \), decreases. Hence, large negative rake angle contributed by larger tool cutting edge radius may result in a poor surface generation, due to excessive ploughing with no chip formation.

Figure 3: Schematic of silicon cutting with various inherent complexities on enabling ductile mode cutting.

Silicon will continue to deform plastically if the dislocation is continuously emitted by the external loading from the cutting tool during machining. In Griffith’s theory of brittle fracture [20], a crack becomes unstable and propagate when the released elastic strain energy situated around the crack tip is larger than the minimum energy associated with the appearance of a free surface. This causes the fracture to occur when the dislocation emission becomes insufficient.
to overcome the material’s fracture toughness, $K_c$. Hence, the effect of strain rate (due to dislocation activity) to enable ductile mode cutting must be considered. The activation energy required for emitting a dislocation per unit length from a crack tip, $\Delta G$, can be computed by [21]:

$$\Delta G = Ab^2 \left[ \ln \left( \frac{Ab}{K_{csi}} \sqrt{\frac{2\pi}{\tau_e}} \right) - 1 \right]$$  \hspace{1cm} (3)

Where $A$ is a constant related to the material property, $b$ is the Burgers vector, and $K_{csi}$ is the dislocation critical stress intensity. From the theory of brittle-ductile transition [22–23], strain rate is found to be proportional to the dislocation velocity and the relationship between the yield stress and dislocation velocity. Hence, the relationship between the activation energy for dislocation emission and the strain rate is:

$$\sigma_y = c\dot{\varepsilon}^n e^{\frac{\Delta G}{k_BT}}$$  \hspace{1cm} (4)

Where $\sigma_y$ is the yield strength, $c$ is a constant, $\dot{\varepsilon}$ is the strain rate, $e$ is an Euler number, $k_B$ is the Boltzmann constant, $n = 2.2$ for uniform deformation condition and $T$ is the temperature. By rewriting Equation 3, the dislocation critical stress intensity factor affected by strain rate is:

$$K_{csi} = \frac{Ab}{e} \sqrt{\frac{2\pi}{\tau_e}} e^{\frac{1}{cn\ln\left(\frac{\sigma_y}{c\dot{\varepsilon}}\right)}}$$  \hspace{1cm} (5)

According to Figure 4, the expression for strain rate is:

$$\dot{\varepsilon} = \left( \frac{\cos \gamma_e}{\cos (\varphi - \gamma_e)} \right) \left( \frac{v_c}{\Delta y} \right)$$  \hspace{1cm} (6)

Where $V_c$ is the cutting speed and $\Delta y = \tau_e \left( \frac{1 - \sin \gamma_e}{\cos \gamma_e} \frac{\cos \varphi}{\cos \gamma_e} \right)$ is the average thickness of the primary shear deformation zone (PSDZ). By rewriting Equation 6, the strain rate is:

$$\dot{\varepsilon} = \left( \frac{1 - \sin \gamma_e}{\cos ^2 (\varphi - \gamma_e)} \right) \left( \frac{v_c}{\tau_e} \right)$$  \hspace{1cm} (7)
By inspecting Equations 6 and 7, smaller critical stress intensity, which promotes dislocation emission, can be achieved by a larger strain rate due to the high cutting speed and small tool cutting edge radius. Increase in the dislocation emission activity also prevents the crack tip from manifesting and thus inhibiting it to propagate.

Figure 4: (a) Schematic of the shear deformation model within the cutting zone and (b) velocity relationship model within the first deformation zone.
3. Experimental Procedure

3.1. Machine Setup and Conditions
Figure 5 shows the Nanowave MTS5R micro-milling system which conducts the experiments. It comprises of a three-axis motion stage with feed precision of 0.1 μm, a high-speed air bearing spindle, a workpiece holder and a dynamometer (Kistler minidyn 9256C) for cutting force measurement. A pre-machining inspection was performed by a dial indicator with a resolution of 1 μm. The inspection was performed by running the dial indicator across the workpiece’s surface and maintain the squareness error between the workpiece and cutting tool below 1 μm with appropriate adjustment. Full slot micro-milling was performed on a 500 μm thick polished (001) silicon wafer, and compressed air was supplied onto the workpiece’s surface to dust off any debris formed during machining. Table 1 shows the parameters employed in this study.

![Figure 5: Nanowave MTS5R micro-milling system.](image)

<table>
<thead>
<tr>
<th>Feed Rate ( f_z ) (μm/tooth)</th>
<th>Cutting Speed ( V_c ) (m/min)</th>
<th>Depth of Cut ( a_p ) (μm)</th>
<th>Feed Direction</th>
</tr>
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<tbody>
<tr>
<td>0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.8, 1, 1.2, 1.4</td>
<td>31.42, 78.54</td>
<td>10</td>
<td>[100], [110]</td>
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</table>

Table 1: Machining parameters employed in the study.
3.2. Micro-End-Mill

A natural diamond end-mill was used in the study, and its corresponding geometries are shown in Table 2. Inspection of the diamond end-mill was not performed due to the manufacturer’s advice on tool breakage without delicate handling process. Hence, the tool edge radius was estimated at 0.1 µm [24].

<table>
<thead>
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<th>Table 2: Tool geometries used in the study.</th>
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<tbody>
<tr>
<td>End-Mills</td>
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<tr>
<td>Nominal Diameter (mm)</td>
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<tr>
<td>No. of Flute</td>
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<tr>
<td>Nominal Rake Angle (°)</td>
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<tr>
<td>Cutting Edge Radius, $r_e$ (µm)</td>
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</table>

3.3. Characterisation Methods

3.3.1. Surface Roughness and Morphology Measurement

An ultrasonic bath was used to clean the machined samples before surface characterisation. A white light interferometer (Zygo NewView 5020) was used to measure the surface roughness of the bottom machined surface. Five measurements were taken from different areas to reduce measurement uncertainty, while an average roughness value ($R_a$) and its respective standard errors were computed. Surface morphology was also analysed using a Scanning Electron Microscope (Hitachi TM3030). Upon machining, the evident appearance of chip adhesion on the diamond end-mill was characterised by the energy dispersive X-ray spectroscopy (EDX).

3.3.2. Edge Chipping Measurement

Conventionally, the qualitative characterisation was performed to analyse the machining-induced edge chipping. Consider the lack of measurement guidelines, attempts to quantify them by measuring either the length or/and width of the chipped edges as illustrated in Figure 6 were used [25–27]. However, such a method cannot objectively quantify the full edge chipping profile. In this study, a volumetric measurement method was proposed. It allows better representation of the edge chipping as the full chipping profile (including depth) is considered.
A 3D focus-variation surface profilometer, Alicona G4, was used for the volume measurement. Due to the polished silicon surface being reflective, acquisition of good dataset was a challenge. Fortunately, it was resolved by a profile duplication process, which transfers the edge chipping profile onto a silicone polymer replica compound with a resolution of 0.1 µm. Figure 7 shows the proposed measurement method using the replica compound and surface profilometer.

Figure 6: Edge chipping length and width commonly defined for measurement.
Figure 7: Proposed process flow for edge chipping measurement on a machined monocrystalline silicon.

Measurement process begins by cleaning the machined (001) silicon surface with isopropyl alcohol (IPA) solvent. It removes any residue chips or dust embedded on the surface, while not affecting the duplicated profile (Step 1). Premixed replica silicone polymer compound was dispensed onto the machined workpiece in the following step. After dispensing, a metal plate was introduced to the replica compound and acts as a base support for the duplicated profile. Upon solidification, the duplicated profile was peeled down for measurement by the surface profilometer (Steps 2 and 3).

The profilometer’s software provides an automated reconstruction of the original profile from the measured duplicated profile. Finally, upon obtaining the 3D dataset along the middle region of each machined slot, “volume measurement” module in the profilometer’s analysis package was used, and measurement was taken on both up and down-milling sides of the slot (Step 4). Measurements were obtained using a 50x objective lens. Five analyses were conducted in different areas to reduce measurement uncertainty, while an average edge chipping volume and the standard errors were computed.
4. Results and Discussion

4.1. Tool Wear Analysis

Figure 8 shows the diamond micro-end-mill characterised by both SEM and EDX after machining. Chip adhesion on the tool surfaces might be associated with the heat generation within the cutting zone during machining [28]. The following scenarios may contribute to heat generation. Firstly, as uncut chip thickness begins to increase at the beginning of each cut, excessive ploughing occurs with no chip formation. This induces high friction between the tool-chip interfaces and thus generates heat. Secondly, kinetic energy supplied by the compressive motion from a negative effective rake angled tool is converted into heat during the material removal process due to plastic deformation.

The high temperature generated within the cutting zone may increase the diffusion rate and chemical interactions between the cutting tool and the silicon workpiece. Figure 8(a) shows a cluster of silicon chips being adhered onto the rake face of the diamond tool. The composition of the silicon chips was verified by the EDX spectrum map as shown in Figure 8(b). Wear on the diamond micro-end-mill was believed to have undergone a series of effects beginning from thermal to the tribo-chemical reaction, and then mechanical. Previous studies have discussed the tribo-chemical reactions contributed by the elevated machining temperature during cutting [29-31]. It comprises of surface oxidation (also observed by the EDX analysis in Figure 8(b)), graphitisation of diamond, and the formation of silicon carbide like particles between the adhered silicon chips and diamond particles can occur under these conditions.

Since silicon carbide is harder than monocrystalline silicon, such an event may lead to the generation of disordered sp³ to sp² bonds due to the abrasion of the silicon carbide like particles onto the diamond micro-end-mill. Hence, the adhered silicon chips and the high temperature generated during machining may accelerate the tool wear and eventually dislodge segments of the tool after some machining time. An evident example was demonstrated by the chipping of the cutting edge as shown in Figure 8(c).

Moreover, previous studies have shown a common wear pattern occurring on the flank face of a diamond turning tool [32–34]. The effect was attributed to the increment of compressive stress in the cutting zone during the chip formation process under ductile mode cutting conditions and the diamond crystal structure [35–36]. Although flank wear was not observed
on the diamond micro-end-mill in this study, its occurrence may affect the machining quality since the tool’s flank face is always in direct contact with the final machined surfaces.

4.2. Surface Generation and Roughness Measurement

In a milling process, ploughing of the tool cutting edge occurs at the beginning of each cutting pass before the uncut chip thickness reaches a minimum value to form the chip. The ploughing process led to a complex deformation on the silicon due to the presence of multiple slip systems and pre-existing crystal defects in the silicon microstructure and was considered as the mechanism which induces dislocation activities during machining [37–38]. As such, proper selection of the machining conditions such as the cutting speed, feed rate and feed direction are required. It will help to promote and increase the dislocation activities that will be useful in shielding the propagation of a crack emitting from a machining-induced crack tip [39].

After machining, the unloading motion of the tool cutting edge relaxes on the final machined surface, and various surface textures were formed. Figures 9 shows the SEM micrographs of

![Figure 8: Surface characterisation of diamond micro-end-mill (a) SEM micrograph of adhered silicon chips, (b) EDX analysis and (c) SEM of chipped tool cutting edge.](image)
typical bottom machined surfaces of the silicon channels. In general, three types of surface defects, namely, the micro-debris, residual flake chips and micro-pitting were observed. Amongst the described defects, the generated surfaces were influenced mainly by the micro-pits. Although they were only present at \( f_z > 0.80 \) \( \mu \text{m/tooth} \) and their concentration increase with the feed rate, each micro-pit may vary up to several tens of micrometres in size.

Quantitative measurements were also performed to analyse the surface roughness using the method described in Section 3.3.1. Figure 10 shows the surface roughness values measured on the bottom machined surfaces of the silicon channels. Arithmetic surface roughness, \( R_a \), which provides information on the average roughness of each respective surface geometries was used to analyse the effect of the surface generation. Under the employed machining parameters, sub-micron-level of surface roughness values have been achieved and are comparable to those in the micro-milling of metals with similar machining system and conditions [40].

As seen in Figure 10, the feed rate has a significant influence on the surface generation, while the machining feed orientation and cutting speed were observed to portray a considerable influence on determining the mode of cutting only at high feed rates. A minimum \( R_a \) value of approximately 20 nm was measured at \( f_z = 0.05 \) \( \mu \text{m/tooth} \), \( V_c = 78.54 \) m/min and the [100] direction. In contrast, the maximum \( R_a \) value of approximately 70 nm was measured at \( f_z = 1.40 \) \( \mu \text{m/tooth} \), \( V_c = 78.54 \) m/min and the [110] direction. Under similar cutting speed and direction, an increase in the \( R_a \) was observed when the feed rate increases.

Moreover, as the [100] direction exhibits higher fracture toughness, better surface finishing was achieved. In contrast to the feed direction and feed rate, an interesting phenomenon was observed on the surface generation of silicon when higher cutting speed was used. According to Equations 6 and 7, machining at higher cutting speeds can generate better surface quality due to an increase in the machining strain rate and dislocation nucleation activity. Such theory was demonstrated by a decrease of up to 20% and 13% on the measured \( R_a \) values, when machined by \( f_z < 0.40 \) \( \mu \text{m/tooth} \) at the [100] and [110] directions respectively. However, when silicon was machined by \( f_z > 0.40 \) \( \mu \text{m/tooth} \), regardless of the feed directions, the measured \( R_a \) values increases with the cutting speed. The underlying mechanism was unknown but was believed to be attributed by the masking effect from tool wear and the dynamic stability of the micro-milling system.
Figure 9: Typical SEM micrographs of silicon bottom machined surfaces by $V_c = 78.54$ m/min along the [100] direction.
Figure 10: Arithmetic surface roughness, $R_a$, measured on the bottom surface of the machined (001) silicon.
4.3. Edge Chipping Formation Mechanism and Measurement

Edge chipping is commonly observed along the surface edges of a final machined product during brittle material machining. It is formed by a community of surface defects and may be comparable to the machined feature size. Its presence may affect the geometric accuracy, structural integrity and electronic functionality of the finished parts. Hence, it can be a challenge to minimise and suppress its development. Edge chipping is formed by the propagation of a crack tip when $K_{cd} > K_c$. Considering a plane strain condition, where mode 1 and 2 loadings are assumed to be present in orthogonal cutting. The stress-intensity factors, $k_1$ and $k_2$, presented around the crack tip, may be extended towards any direction in a plane that is in the normal direction to the crack tip, thus causing it to be curved. However, it also depends on other machining conditions [41–43].

Yan et al. [44] discussed the influence of feed rate on the formation of subsurface damage on silicon and suggested that the formation mechanism undergoes the following procedures starting with amorphisation, the formation of poly-crystallisation, development of micro-cracks and the formation of dislocation lines. During cutting, a compressive motion of the tool cutting edge causes the silicon to change into a metallic phase. After the tool advances, the compressed silicon transforms into an amorphous phase, thus leaving a thin layer of $\alpha$-Si on the workpiece surface. Domination of shear and tensile stresses will occur beyond the brittle to ductile phase transition region, thus promoting the development of micro-cracks.

When a micro-crack tip is generated, results from Yan et al. [44] showed the extension of the fracture deeply into the crystalline bulk substrate. As the fractured crack tip is subjected to both normal and tangential load upon contact by the cutting tool, a significant concentration of residual tensile and shear stresses will form around the cutting zone. This induces the formation of profound dislocation line defects and may develop into internal micro-cracks when machining at higher feed rates. In conjunction with the mechanism as discussed in Figure 2, machining at lower feed rates will cause the fracture to occur at the upper edge of the cut shoulder and help to prevent any further internal propagation. Therefore, the developed fractures can be removed by the subsequent tool cutting passes, which in turn produces fewer surface defects and hence achieving ductile mode cutting performances.
Figure 11 shows the modes of edge chipping observed on micro-milled silicon. As indicated by the block arrows, these were categorised as 45°, 90° and mixed mode chippings. The angles indicate the direction of crack propagation from the plane normal to the crack tip. Mixed mode chipping reported by irregular propagations of the crack tip mainly dominates the surface edges of the machined silicon. Its dominance may be contributed by the instantaneous rotation of the cutting tool during milling, and the instability contributed by poor machining conditions during cutting, thus resulting in a distribution of non-uniform stress field on the crack tip.

For the 45° and 90° chippings, they were briefly observed along the [100] and [110] directions respectively. The mechanism of such effect was believed to be attributed by shear deformation, where its anisotropic behaviour was demonstrated by the direction of the Tresca maximum shear stress and the subsurface damage analysis in Wang et al.’s work [42]. In a (001) silicon, dislocations and micro-crack tips are generated by the shear stress acting on the {111} <110> slip systems and the {111} primary or {110} secondary cleavage planes respectively. Hence,
the fracture energy will transverse towards the easiest cleavage planes, at 45° and 90° when cutting was performed at the [100] and [110] directions respectively on a (001) silicon.

Ladder-like profiles, intersecting the {111} family cleavage and slip planes were also observed, regardless of the chipping modes. This was also due to the crystallographic structure of silicon having low surface energies that run along its cleavage and slip planes, where a crack can no longer be contained during machining. Under similar machining conditions, the size of edge chipping developed along the down-milling sides was generally more extensive than those produced along the up-milling sides.

Such an effect was due to the uncut chip thickness, $t_c$, decreasing from a large value towards zero in a down-milling process. The value is usually larger than the ductile to brittle transition chip thickness, $t_d$, thus causing the material to experience premature fracture on the final machined surface. As such, even at a small feed rate, $f_z$, substantial machining stress induced at the beginning of the down-milling causes the crack to develop closer towards the final machined surface. This eventually leads to massive subsurface damage. Similarly, the mechanism can also be used to explain the increase in edge chipping when the machining feed rate increases.

Quantitative measurement of the edge chipping was conducted using the method described in Section 3.3.2. Selected 3D profiles of the surface edge on the up-milling side of the machined silicon channels that were extracted for measurements are shown in Figure 12. Subsequently, selected SEM micrographs of the machined silicon channels are also shown in Figure 13 for comparison with the measurements. In this investigation, the type and quantity of the surface defects (including edge chipping) are used as the qualitative marker to characterise the achieved mode of cutting.
Regardless of the feed direction and cutting speed, surface with ductile textured characteristics that exhibits uniform machining marks and absence of any surface defects were predominantly observed when machining by smaller feed rates, $f_z < 0.4 \, \mu m/tooth$ (E.g. Figures 13(a), (b), (f), (g), (k), (l), (p), (q)). Formation of several surface defects and moderate edge chipping as shown in Figures 13(c), (d), (h), (i), (m), (n), (r) and (s) can be regarded as the achievement of partial ductile mode cutting. In contrast, severe generation of the machining-induced edge chipping as shown in Figures 13(e), (j), (o) and (t) were regarded as the brittle cutting mode.

Down-milling generally generates larger edge chipping and was especially evident at higher feed rates. Therefore, only the edge chipping developed on the up-milling side were measured. Furthermore, even though the axial depth of cut was constant in this investigation, it was worth noting that the workpiece surface might not be entirely levelled. Hence, the measured volumes were normalised by the experimental axial depth of cut, $a_p$, at 10 $\mu m$. Figures 14 shows the measured volumes of the edge chipping developed along the up-milling side of the machined silicon channels.

The feed rate was observed to have a significant influence on the generation of edge chipping, while the machining feed orientation and cutting speed were observed to portray considerable influence only at higher feed rates, $f_z > 0.40 \, \mu m/tooth$. A minimum value of edge chipping of approximately $80 \, \mu m^3$ was measured at lower feed rate ($f_z = 0.05 \, \mu m/tooth$), higher cutting speed ($V_c = 78.54 \, m/min$) and the [100] direction, while the maximum value of edge chipping of approximately $1000 \, \mu m^3$ was measured at higher feed rate ($f_z = 1.4 \, \mu m/tooth$), lower cutting speed ($V_c = 31.42 \, m/min$) and the [110] direction.
In general, the size of edge chipping increases with the increase in the feed rate. Regardless of the cutting speed and feed direction, an insignificant increase in the size of edge chipping measured between 80 and 350 µm³ was observed at lower feed rates, \( f_z < 0.40 \, \mu \text{m/tooth} \). However, a significant increment of up to 1000 µm³ in edge chipping was observed at higher feed rates. Furthermore, similar anisotropic influence on the surface generation was also observed on the generation of edge chipping. Due to the anisotropic structure of the (001) silicon, the <100> family directions exhibit higher fracture toughness. Therefore, smaller edge chipping was expected along the [100] direction.

Despite so, the anisotropic influence on the edge chipping generation was small and negotiable at lower feed rates, \( f_z < 0.40 \, \mu \text{m/tooth} \). Not only does this suggest that machining silicon at lower feed rate minimises the edge chipping, but indications on the weakening of the anisotropic influence at lower feed rate also suggests the opportunity for greater flexibility in machining path planning. Regarding the cutting speed, its impact on edge chipping tends to corroborate with the surface generation mechanism. Under similar feed direction and feed rate, a maximum reduction of up to 10% on edge chipping was observed. Considering the machining strain rate, this may be attributed to the promotion of plastic deformation due to the increasing dislocation activities. Therefore, higher cutting speed should be employed for better machining efficiency.

Also, the development of an edge chipping minimisation method as described by Ng et al. [25] through the construction of a sandwich support structure using epoxy during silicon cutting is also encouraged. Such an approach may potentially improve the machining efficiency by allowing silicon to be machined under larger feed rate and axial depth of cut.
<table>
<thead>
<tr>
<th>$f_z$ (µm/tooth)</th>
<th>Image</th>
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</thead>
<tbody>
<tr>
<td>0.05</td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
<td>(d)</td>
<td>(e)</td>
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<td>(m)</td>
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$V_c$ = 31.42 m/min [100]

$V_c$ = 31.42 m/min [110]

$V_c$ = 78.54 m/min [100]

$V_c$ = 78.54 m/min [110]

Figure 13: Selected SEM micrographs of machined silicon channels.

- Interior edge chipping
- Micro-pits
Figure 14: Normalised edge chipping volume measured along the up-milling side.
4.4. Cutting Force Analysis

Cutting force is also a useful indication to identify the material removal mechanism. Under ductile mode cutting conditions, chip formation by plastic deformation yields a higher thrust force, $F_t$, than the cutting force, $F_c$ [46]. This is because very small uncut chip thickness, and depth of cut are often employed in micromachining operations when compared to the machining at conventional scales. When the uncut chip thickness, $t_m$, is approximately equal to the tool cutting edge radius, $r_e$, the effective rake angle turns negative as shown in Equations 1 and 2. As such, the presence of the negative rake angle can contribute to the generation of large pressure stress field on the substrate surface, causing a rise in the thrust force, $F_t$.

According to the theory of plasticity, the magnitude of thrust force, $F_t$, usually determines the degree of plastic deformation and therefore can be used to characterise to the achieved cutting mode. Both thrust force, $F_t$, and the cutting force, $F_c$, can be computed by the measured feed, $F_f$, and cross-feed, $F_n$ forces using Equations 8 and 9 respectively [47].

\[
F_t = F_f \sin \theta + F_n \cos \theta \tag{8}
\]

\[
F_c = F_f \cos \theta - F_n \sin \theta \tag{9}
\]

Where $\theta$ represents the immersion angle of the cut.

Figure 15 shows the selected $F_t$ and $F_c$ computed from the corresponding surfaces as shown in Figures 13(k) and 13(o) respectively. The behaviour of the measured signals was observed to correspond with respective surface morphologies. Regardless of the feed direction, ductile textured surface as shown in Figure 13(k) was denoted by the stable force signal in Figures 15(a) when cutting was conducted at the small feed rate, $f_z = 0.05 \, \mu m/tooth$. Furthermore, the presence of $F_t > F_c$ indicates the generation of considerable compressive stress in the cutting zone to suppress crack propagation [46].

On the contrary, Figure 15(b) shows an increase in the intensity and instability of the force signal when the feed rate increases. The effect was due to the increased chip area being removed and the potential stability issues with the machine dynamics at higher feed rate. Despite the presence of chattering along the peaks of the measured force signals, the signal shape was relatively structured. Moreover, the amplitude of the cutting force, $F_c$, was observed
to be larger than the thrust force, $F_t$. Such effect also signifies the presence of brittle cutting mode at higher machining feed rates.

By comparing the behaviour of the cutting forces with the finishing of the respective machined surfaces as discussed in the previous sections, stable cutting force achieved by small feed rate helps to improve the surface quality and removal efficiency. Conversely, chaotic forces and chattering obtained at large feed rate denotes the occurrence of irregular vibrations in the machining process. This may lead to non-uniform stress loading within the cutting zone and thus promote the growth of micro-fractures.

Specific cutting energy (SCE) is the energy taken to remove a unit volume of the material and can be used as an indicator to observe the brittle-ductile transition. Wang et al. [48] show that material removed by plastic deformation requires a higher SCE than a brittle fracture. Hence, brittle mode machining can be expected when the SCE falls towards a low steady-state value. Using the computed thrust force, $F_t$, and the cutting force, $F_c$, SCE, $U$, can then be calculated using the trapeze integration method shown in Equation 10 [49]:

$$ U = \frac{v_c}{V_{rem}} \times \int_0^{T_c} \sqrt{F_t^2 + F_c^2} \, dt \quad (10) $$

Where $V_c$ and $V_{rem}$ are the cutting speed (m/min) and the material removal volume (mm$^3$), while $T_c$ is the cutting time (seconds).

Figure 16 shows the tabulated SCE at selected cutting speed and feed direction. Regardless of the machining parameters, higher specific cutting energy symbolising the dominance of ductile mode machining were observed at $f_z < 0.40 \, \mu m/tooth$. The effect was attributed to the shearing of material by the tool cutting edge along a defect-free plane under small machining scale. Moreover, the exceptionally high SCE at $f_z = 0.05 \, \mu m/tooth$ could be explained by the potential dominance of ploughing. This is because the energy consumed does not entirely contribute to the chip formation process, but instead to ploughing and the generation of interfacial friction between the tool flank face and newly machined surfaces.
As the feed rate increases between $0.40 \, \mu m/\text{tooth} < f_z < 0.60 \, \mu m/\text{tooth}$, the variation of energy consumption during cutting begins to subside. Such an effect was characterised as the transition between ductile to brittle machining mode due to subtle increment in cutting forces caused by the occurrence of partial brittle fracture. Ultimately when the uncut chip thickness reaches its critical value at $f_z < 0.60 \, \mu m/\text{tooth}$, the SCE becomes relatively stable. The effect was attributed to the unstable cutting forces caused by large fluctuations during the continuous development of brittle fractures.

Also, higher SCE were observed along the [100] feed direction and at $V_c = 78.54 \, \text{m/min}$. The phenomenon was due to the crystalline structure of silicon having more robust atomic bonds along the robust $<100>$ directions, and that larger activation energy to promote dislocation activity at higher cutting speeds also contributes to the overall cutting energy.

![Figure 15](image-url)

**Figure 15:** Selected thrust, $F_t$, and cutting, $F_c$, force data measured at the [100] direction by (a) $V_c = 78.54 \, \text{m/min}, f_z = 0.05 \, \mu m/\text{tooth}$ and (b) $V_c = 78.54 \, \text{m/min}, f_z = 1.4 \, \mu m/\text{tooth}$.
Figure 16: Experimental specific cutting energy for diamond micro-milling on (001) silicon on selected machining parameters.
5. Conclusion

This study investigates the machinability and edge chipping mechanism on (001) silicon wafer through diamond micro-milling. Machining feed rate and axial depth of cut of higher orders comparing to previous researches were employed for enhanced efficiency. Furthermore, improving the machinability of silicon relies on ensuring plastic deformation to occur through appropriate control of the machining parameters. Hence, several conclusions from this study were drawn:

1. Tool wear is an inevitable issue and was observed in this investigation. Adhesion of the silicon chips onto the diamond micro-end-mill was believed to be attributed by the elevated machining temperature during cutting, thus resulting in material diffusion between the tool and workpiece. Furthermore, the heat may also lead to a tribo-chemical change on the natural diamond, which leads to graphitisation. As a result, it accelerates the abrasion wear and causes dislodgement of the cutting edge after some machining time.

2. A volumetric measurement technique was proposed to quantify edge chipping. Three chipping types: 45°, 90° and mixed mode were observed. Its mechanism is attributed to the intersection of radial cracks at 45°and 90° along {110} family cleavage planes and lateral cracks along {111} family slip planes. Mixed mode chipping was mainly observed, while the 45° and 90° chippings were briefly observed along <100> and <110> family directions respectively. Ladder-like steps can also be observed in the chipped profile.

3. Several surface defects such as micro-debris, micro-pitting, residual flake chips and irregular streaks were observed to develop under specific machining parameters. Amongst the controllable factors, results showed that the feed rate has a significant influence on the primary material removal mode. When machining at smaller feed rates, \( f_z < 0.4 \mu \text{m/tooth} \), ductile textured surfaces often defined by the presence of uniform machining marks and absence of any surface defects were observed.

4. The cutting speed and feed direction also have considerable effects on the surface generation. In addition to machining with small feed rate, experimental results show that the arithmetic surface roughness, \( R_a \), and edge chipping volume of approximately 20 nm and 80 \( \mu \text{m}^3 \) were achieved with high cutting speed and the [100] feed direction. The effect was attributed to the improved plasticity that enhances the yield strength and fracture resistance of the silicon workpiece during cutting.
References


